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SCINTILLATING FIBRE DETECTOR SYSTEM FOR SPACECRAFT COMPONENT DOSIMETRY

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Abstract

A general purpose nuclear detector is presented, based upon a scintillating fibre sensor in a non-pulsed mode. It is combined with a photodiode and a logarithmic current amplifier, both exhibiting extremely low background noise. Excellent linearity and dynamic range are observed.

1. INTRODUCTION

The operating constraints of common nuclear radiation detector types such as Ion chambers, Geiger counters, solid-state detectors, scintillator-photomultiplier combinations and various dose meters are quite well known and their use is widespread. For applications demanding a minimum of instrument complexity, power consumption and weight, like spacecraft electronic system monitors or portable general-purpose radiation detectors, none of the usual detectors simultaneously comply with requirements like:

- operation at low power consumption, without high voltage supply
- compact electronics, not requiring any adjustment or calibration
- high detection sensitivity, combined with long-term operation
- pulse mode operating option for energy/particle discrimination
- very high dynamic range of linear radiation flux measurement
- immunity to high transient doses and other kinds of radiation.

For measurement and monitoring in space of high energy proton and electron radiation with a widely varying flux, the European Space Agency (ESA) has initiated the development of a general-purpose nuclear detector suitable for miniaturisation, a low power budget and most important, a very wide dynamic range in order to detect the causes of electronic system components malfunctions in orbit.

Fibre dosimeters for spacecraft and other applications have been reported [1,2,3] but these employed the principle of loss of transmission as a result of radiation induced 'darkening'. Scintillating fibres in the pulsed mode are common in high energy physics, see for example [4,5]. The scintillating fibre reported here operates in a novel mode compared with previous applications.

2. DESCRIPTION

2.1 General Description

The system consists of a probe with renewable scintillating fibre used in NON-PULSED mode, a polystyrene fibre-optic cable 1-100 m. long to connect the scintillating probe to a remote preamplifier module, and a portable control computer equipped with an A/D converter.

The module can either be directly coupled to the portable PC, or be used externally via an electrical ribbon cable of 1 to 10 m length.

A complete data analysis and systematic error correction program provides full graphical and numeric presentation of experimental data, as well as archiving of all data collected during tests. It also provides for self-calibration after entry of particle type and/or radiation energy, by using mathematical corrections of the detected average scintillation intensity and for the measured temperature.

2.2 Working Principle

The Scintillating Fibre Nuclear Detector is based on the scintillation properties of thin extruded plastic fibres doped to obtain response to, amongst others : beta, X-ray, gamma, proton and heavy ion radiation of sufficient energy to penetrate the thin wall (0.2 mm) of the aluminium light screening tube of the fibre, or the 0.04 mm surface layer on a bare fibre.

The beta response threshold, due to the light-tight aluminium tube, commences at approximately 0.2 MeV, for

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protons at 5MeV, and for gammas at 10 keV. Lower energy radiation, alpha particles and heavy ions can be detected with bare scintillating fibres, for example arranged in a flat coil, covered by a light-tight sheet of thin beryllium foil. Scintillation light generated is detected at one end of the fibre by means of a GaAsP photodiode. The other end is provided with a miniature aluminium reflector to enhance response and to reduce dependence of detector sensitivity on excitation distance, caused by the (partial) self-absorbtion of the scintillation light. High baseline stability (0.2 fA) and wide dynamic range (over 10 decades of photo current) are achieved by design of a solid-state electrometer amplifier with a logarithmic response, combined with a photodiode exhibiting an extremely low leakage current. This saturation current is proportional to exp(kT/qVb), so inherent with the high bandgap energy q.Vb of the semiconductor. The result is a very low background current noise (less than 300 photo-electrons/sec).

Fibre response to 1 MeV gamma, 50 to 300 MeV proton, 3 MeV beta and various heavy ion species at 66 to 167 MeV have been verified at a wide range of dose rates, using the same type of scintillating fibre for all measurements. Good linearity has been found for each kind of radiation up to the highest dose rates, for example with gamma rays from below 1 to more than 100 Rads per minute. Baseline instability even after high fluxes is below 2 µRad/sec. Figs. 1 to 5 show the fibre response to different types of radiation. An apparent decrease in the low-flux response to ions (Fig. 1) is probably due to readout limitations. The reduced response at high electron fluxes (Fig. 3) is due to radiation damage to the fibre material, leading to a difference in response to short pulses (which remained linear) and the response after extended exposure.

Fig. 4 shows the fundemental proton energy dependence of the scintillation efficiency, which appears to be proportional to radiation damage rate. For space applications where the proton energy spectrum varies widely, a scintillating fibre system without a built-in energy discriminator (for simplicity) will give a proton intensity signal indicative of proton damage. High fluxes are measured with an integration time of 10 seconds. The system should be capable of recording flux transients with a response time of 1mS using a D/A controlled recorder output.

2.3 Technical Description

The detector probe consists of a thin-wall aluminium light screen tube (2 mm diameter, 1.6 mm inside) fitted with a fibre of 1 mm diameter and 100 mm length, suitable for easy exchange of fibres. At one probe end a highly polished aluminium reflector of 1.6 mm diameter is mounted into the tube by compression with epoxy sealing, at the other end a fibre-optic SMA connector for 1mm fibres is mounted. Both fibre end faces are optically smooth. Lowest noise from the detector- and amplifier leakage currents is achieved by computer-controlled bias and compensation techniques, based on mathematical correction for all input current components and their respective "activation energies". The photodiode is biased at its point of lowest NEP (noise equivalent power), below zero bias, to avoid the increase by exchange current noise with a factor $\sqrt{2}$ at zero bias.

In addition the effective resolution of the 14-bit A/D converter is increased by software averaging with spurious data rejection, relying on the fundamental properties of signals with added noise, and sufficient stability of the A/D bit transition levels. In this way, the A/D resolution is increased to beyond 16 bits, while the A/D and detector reference voltages are related by software comparison (ratiometry) to further increase accuracy. To avoid noise and thermal disturbances, the photodiode and amplifier are built in a well-screened modular aluminium box, connected to a dedicated computer system provided for data display and analysis. The developed data presentation and storage program takes care of the system self-start, self-calibration and calculation of equivalent photocurrent or radiation flux from the A/D converter data. After temperature correction, it displays the radiation level (in numerical and graphical form) as a function of time. On command the data can be saved to file for any defined period.

3. RESULTS

Photocurrent range	: linear from 0.01 fA to > 100 nA
Baseline stability	: typically 0.2 fA/10 min, 1 fA long-term
Detection limits (approximate)	: 0.04 fA (250 electrons/sec) rms 110 beta particles/sec @ 3 MeV 6 protons per second @ 50 MeV 27 ions Ar8+ /sec @ 176 MeV 5 ions N15++ /sec @ 66 MeV below 1 microRad/sec Co60
Irradiation limits (linearity range)	: beta 100 nA/cm^2 short-term at 3 MeV protons > 1 pA/cm^2 (50-300MeV) ions 30 nA/cm^2 short-term (66-176MeV) gamma > 100 Rads/min at 1 MeV
Dose limit	: estimated to be in excess of 1MRad
Power consumption	: < 100mW from 12 V dc supply
Total mass	: 185 grams (module, probe & cables)

note : detection limits are measured with beam on / off methods. data collected at :
the University of Louvain (heavy ions) Fig.1;
Estec (Co-60) Fig. 2;
IRI Delft (electrons) Fig. 3;
PSI Villigen (protons) Figs 4 & 5.

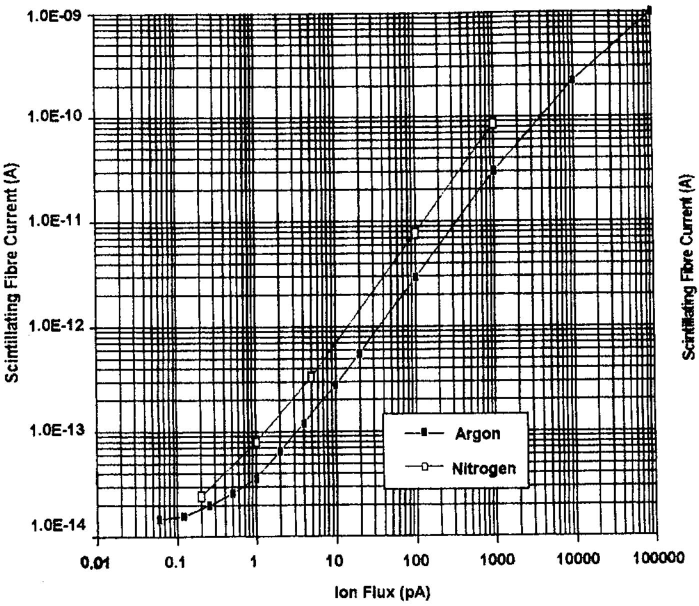

Fig. 1 Scintillating Fibre Response to Heavy Ions

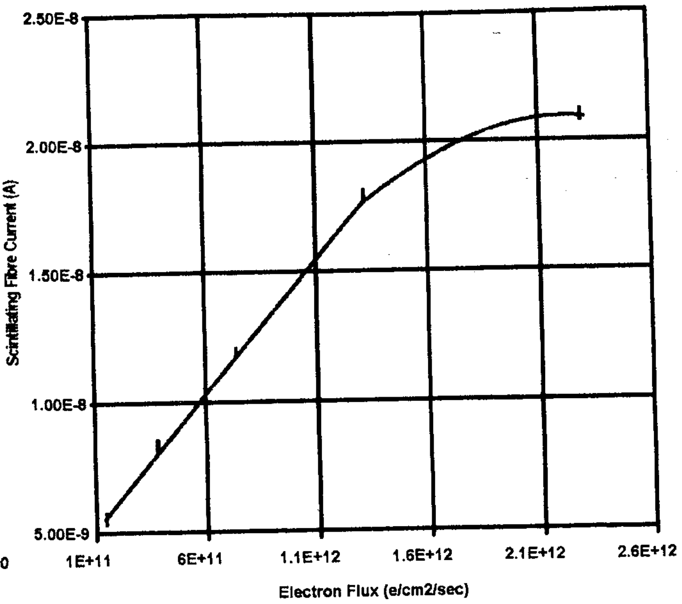

Fig. 3 Scintillating Fibre Response to 3MeV Electrons

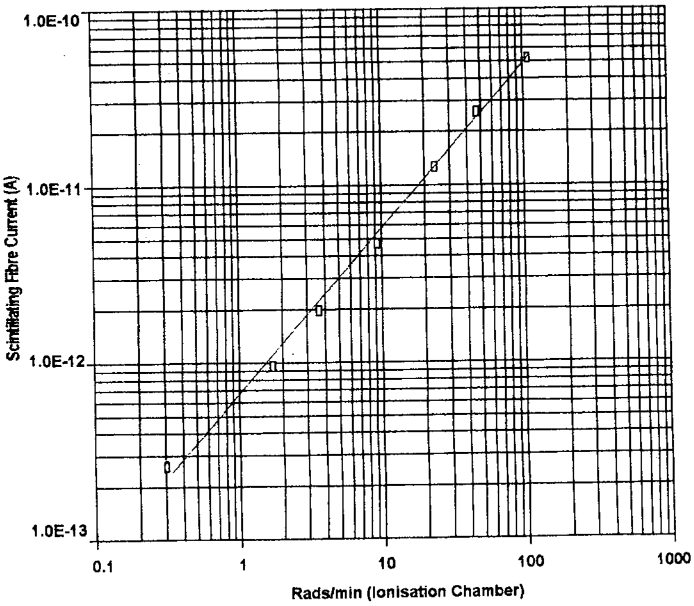

Fig. 2 Scintillating Fibre Response to Co-60 Source

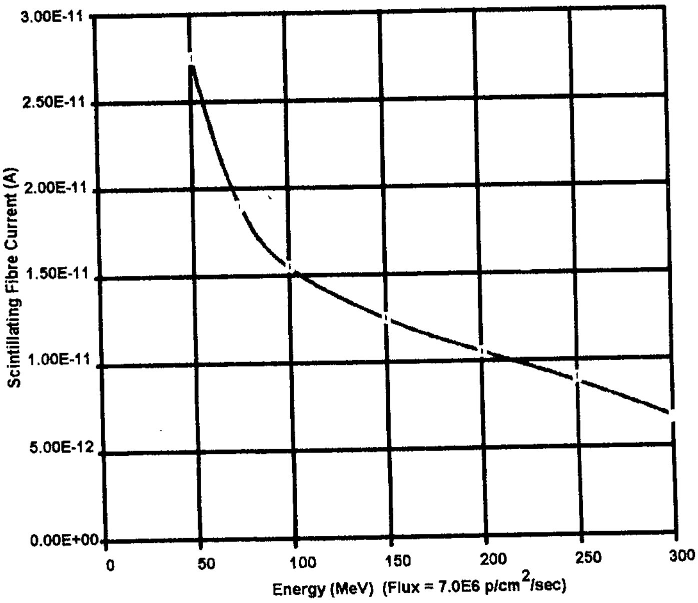

Fig. 4 Response to Constant Proton Flux

4. *APPLICATIONS*

SPACE
personnel (suit) dosimeter
radiation environment monitoring
electronic equipment dose measurement

PHYSICS
accelerator beam-profile monitor
general purpose radiation detector

MEDICAL
eye irradiation beam positioning
in-vivo (skin, artery) dosimeter
medical treatment on-line dosimeter

INDUSTRIAL
industrial safety monitoring
submerged radiation source monitoring

NUCLEAR
nuclear plant cooling systems
sea bottom waste radiation surveys

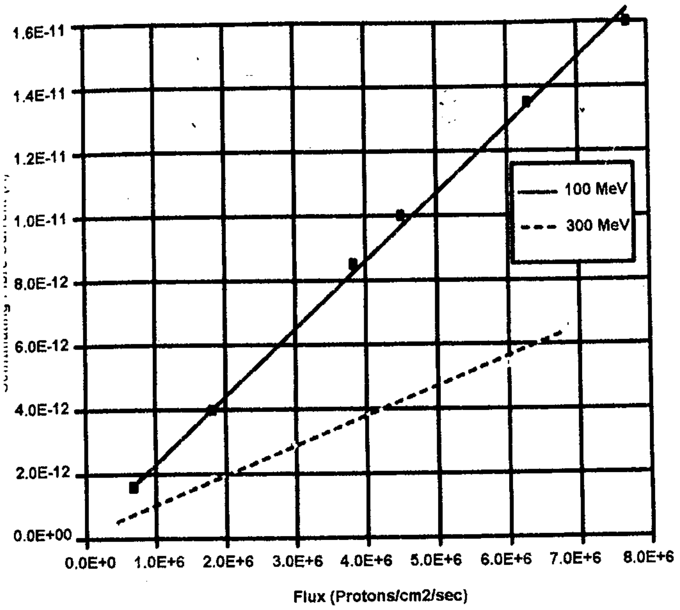

Fig.5 Scintillating Fibre Response to Protons

5. *FURTHER DEVELOPMENTS*

A hybrid circuit version of the scintillating fibre detector is now being developed for space applications and multichannel systems, to achieve spatial and energy resolution.

By applying coincidence counting of pulses received at both ends of the fibre, using pulse height/pulse length analysis, energy and particle type as well as spatial information can be obtained.

In parallel to this development, a preliminary study of a fully bipolar (more radiation-hard) electronic circuit for the detector pre-amplifier has been started. Special attention will be paid to the input circuitry to avoid leakage currents due to total dose damage and spurious responses of the pre-amplifier due to energetic particles. Studies are presently being performed to determine if the reduced dynamic range needed for space application might allow the use of a standard spacecraft analog telemetry channel with 8 bit conversion in the data handling system.

6. *CONCLUSIONS*

Contrary to expectations that analogue (non-pulsed) detectors are some orders of magnitude less sensitive than photon/particle "counting" systems, our results show that they are comparable in sensitivity. Moreover this detector has a much higher linear dynamic range and radiation tolerance coupled with lower system complexity.

This can be attributed (in part) to the advances in low-level current amplifier techniques, and to the higher quantum efficiency of modern photodiodes, relative to photomultipliers.

Moreover, a pulse amplitude / pulse duration discriminator system is foreseen as a viable option by providing the existing low-current, low-noise log amplifier with a fast pulse output.

The use of thin fibres, non-vulnerable to handling, high transient radiation doses and other radiation, proved to be very convenient in use as a particle detector and beam-profile monitor.

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